Exploring Background Contributions in $H \to Z\gamma$ Decay

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Plan

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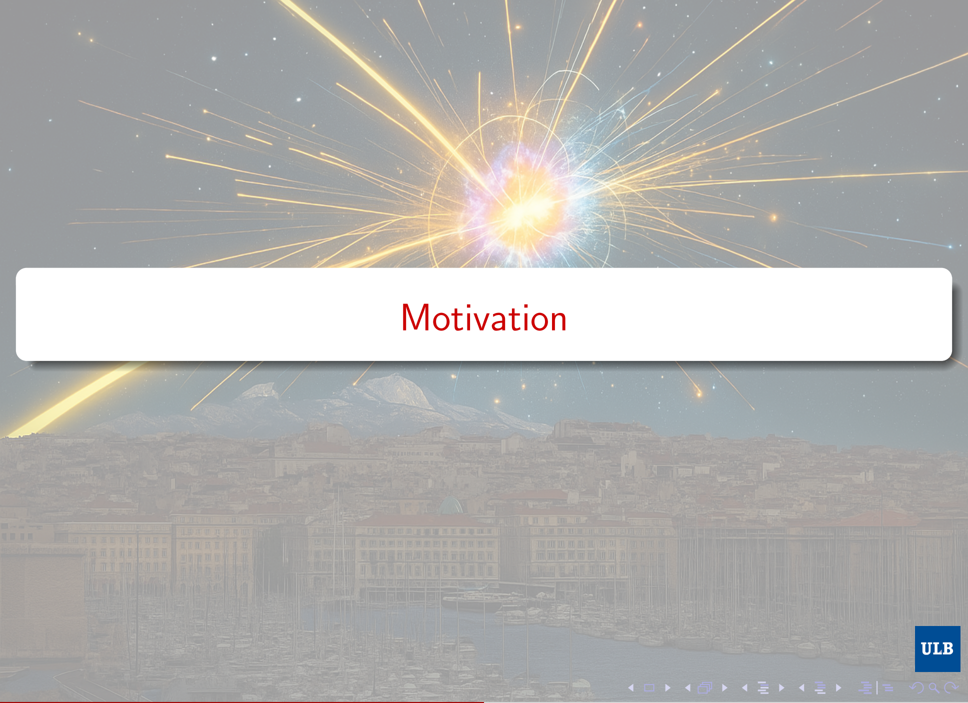

Motivation

Motivation

- Rare Standard Model (SM) processes may shed light on open questions, such as dark matter, baryon asymmetry, and neutrino masses.
- The decay $H \to Z\gamma$ is a rare process within the SM.
- ATLAS and CMS reported a branching fraction of $(3.4 \pm 1.1) \times 10^{-3}$ for $H \to Z\gamma$ process, which is higher by a factor of 2.2 ± 0.7 compared to the SM prediction.
- The excess has been interpreted as a modification of the $HZ\gamma$ vertex.
- Detectors measure $H \to \ell\ell\gamma$; excess events may also be due to new physics (NP) backgrounds.

The content of this talk closely follows the analysis in [arXiv:2503.08659] (published in: JHEP 06 (2025) 043), in collaboration with J. Kimus (ULB), S. Lowette (VUB, IIHE), and M.H.G. Tytgat (ULB).

Motivation

- EFT and UV-complete models responsible for the branching fraction of $(3.4 \pm 1.1) \times 10^{-3}$ for $H \to Z\gamma$.
- Methods to falsify background scenarios.
- Constraints on our models from other observed phenomena.

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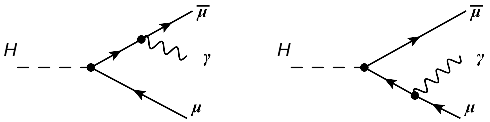
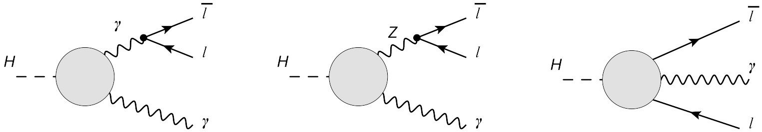
Theory

Theory. The SM



(a) (b)

Tree-level amplitude. Due to the small electron Yukawa coupling, this contribution is relevant only for the dimuon channel.



(c) (d) (e)

Loop amplitudes (schematic) contributing to $H \to \ell\ell\gamma$.

Theory. The SM

- The one-loop amplitude can be expressed as [arXiv:2001.06516]

$$\mathcal{M}_{\text{SM,loop}} = \Big[(q_\mu p_{1\nu} - g_{\mu\nu}\, q\cdot p_1)\bar{u}(p_2)\big(A_1\gamma^\mu P_R + B_1\gamma^\mu P_L\big)v(p_1) \\ +(q_\mu p_{2\nu} - g_{\mu\nu}\, q\cdot p_2)\bar{u}(p_2)\big(A_2\gamma^\mu P_R + B_2\gamma^\mu P_L\big)v(p_1)\Big]\varepsilon^{*\nu}(q)\,,$$

- Tree level

$$\mathcal{M}_{\text{SM, tree}} = -\frac{e^2 m_\mu \varepsilon^*_\nu(q)}{2m_W \sin\theta_W} \times \left[\frac{\bar{u}(p_1)(\gamma^\nu \not{q} + 2p_1^\nu)v(p_2)}{t - m_\ell^2} - \frac{\bar{u}(p_1)(\gamma^\nu \not{q} + 2p_2^\nu)v(p_2)}{u - m_\ell^2}\right].$$

Theory. The NP contribution

- On the level of effective field theory, the contribution to the $\ell\ell\gamma$ background is described by a dimension-8 effective operator [arXiv:1008.4884]

$$\mathcal{L}_{\text{eff}} \supset \frac{g'}{\Lambda_R^4} |H|^2 \partial_\nu (\bar{\ell}_R \gamma_\mu \ell_R) B^{\mu\nu} \, .$$

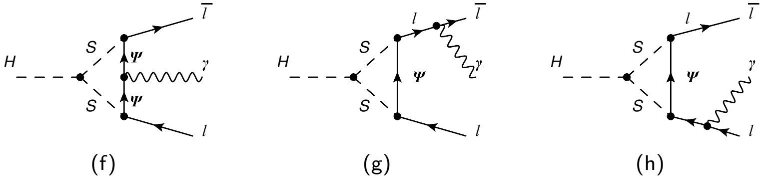
- Other effective operators also contribute to the $H \to \ell\ell\gamma$ process.

Theory. The NP contribution

- One of possible UV-complete solution which can provide missing events described by the Dark matter model [arXiv:1405.6921]

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 + \bar{\Psi}(i\not{D} - m_\Psi)\Psi - \sum_\ell (y_\ell S \bar{\Psi}\ell_R + h.c.) - \frac{\lambda_{hs}}{2} S^2 |H|^2$$

- This Lagrangian gives rise to three new Feynman diagrams contributing to $H \to \ell\ell\gamma$



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Phenomenology

Phenomenology

General overview

- The experimental branching fraction can be obtained for the scale $\Lambda_R = 246$ GeV.
- In the UV-complete theory, there are 4 new parameters that impact the decay rate.
- One solution can be at $m_\Psi = m_S = 62.5$ GeV with the $\ell S \Psi$ vertex coupling $y_\ell = 1.66$ and HSS vertex coupling $y_{hs} = 0.26$.
- Another scenario: $m_\Psi = m_S = 100$ GeV with $y_\ell^2 \cdot y_{hs} = 28.1$.

Phenomenology

Definition of resonant contribution

- The loop contribution consists of resonant and non-resonant parts [arXiv:2109.04426]:

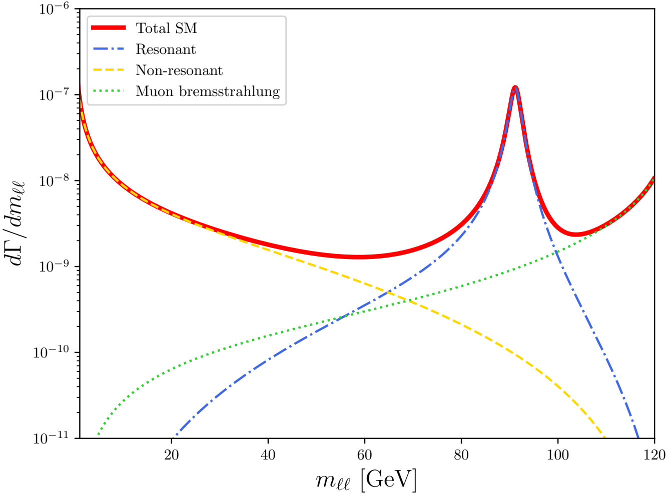
$$a_{1(2)}(s,t) = a^{nr}_{1(2)} + a^{res}_{1(2)}(s)\,,$$

where

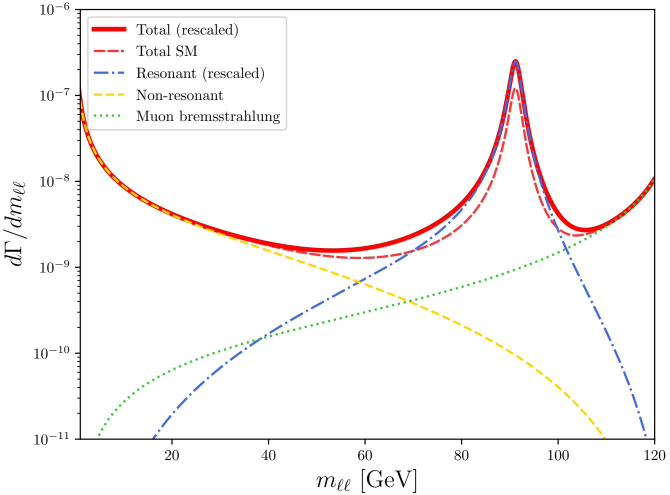
$$a^{nr}_{1(2)} \equiv \tilde{a}_{1(2)}(s,t) + \frac{\alpha(s) - \alpha(m_Z^2)}{s - m_Z^2 + i m_Z \Gamma_Z}, \qquad a^{res}_{1(2)}(s) \equiv \frac{\alpha(m_Z^2)}{s - m_Z^2 + i m_Z \Gamma_Z}\,.$$

Phenomenology

- The resonant contribution corresponds to the process $H \to Z\gamma$, while the non-resonant contribution includes box diagrams and $H \to \gamma\gamma$.



- To simulate the differential decay rate from the experiment, we rescale the resonant contribution in the process $H \to \ell\ell\gamma$.



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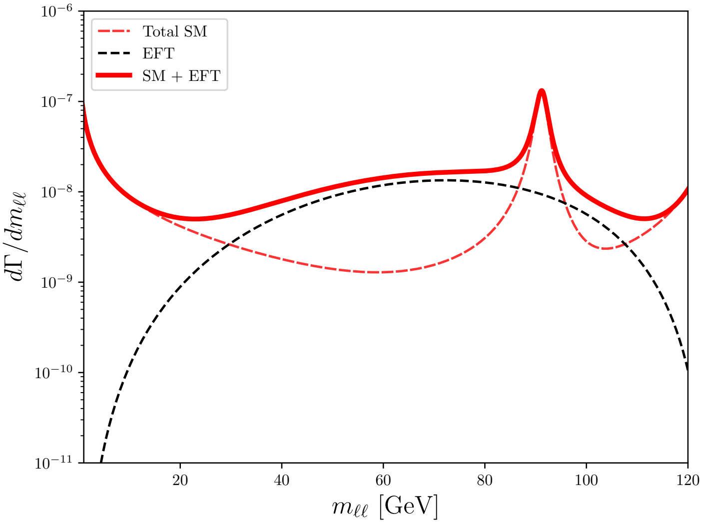
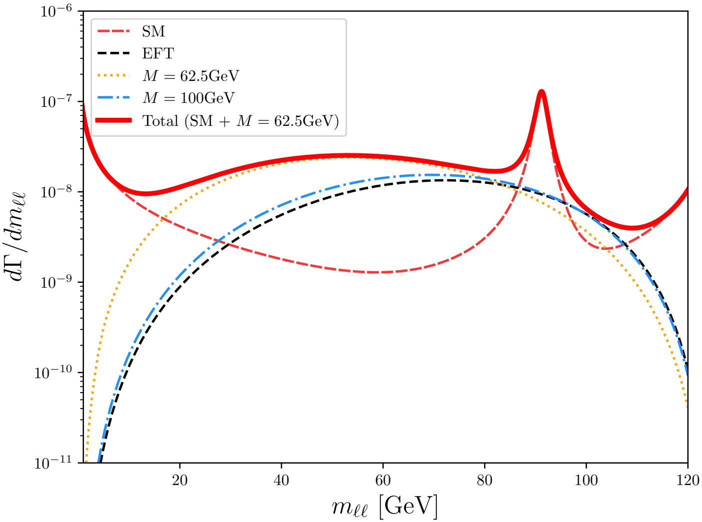
Effective operator

The differential decay rate with the contribution of the effective operator.



Phenomenology
UV-complete theory

The differential decay rate with the contribution of the UV-complete theory.



Theoretical decay rates and the experiment-to-theory ratio for a typical choice of cuts.

#	Cuts	$m_{\ell\ell}^{min}$	$m_{\ell\ell}^{max}$	$\Gamma_{\rm tot}^{\rm SM}$	$\Gamma_{\rm tree}^{\rm SM}$	$\frac{Br_{\rm resc}}{Br_{\rm SM}}$	$\frac{Br_{\rm EFT}}{Br_{\rm SM}}$	$\frac{Br_{\rm UV}}{Br_{\rm SM}}$
1	None	50	125	0.768	0.287	1.67	1.86	2.07
2	None	50	100	0.504	0.028	2.01	2.21	2.57
3	CMS	40	125	0.455	0.011	2.04	2.10	2.13
4	**CMS**	**50**	**125**	**0.451**	**0.011**	**2.06**	**2.06**	**2.06**
5	CMS	70	125	0.440	0.011	2.07	1.80	1.71
6	CMS	70	100	0.432	0.006	2.08	1.74	1.68
7	CMS	80	100	0.416	0.005	2.09	1.48	1.39

Table: CMS cuts: $E_\gamma \geq 15$ GeV, $E_1 \geq 7$ GeV, $E_2 \geq 25$GeV and $t_{min}, u_{min} \geq (0.1 m_H)^2$. $m_{\ell\ell}^{min(max)}$ are in GeV, $\Gamma^{SM}_{\rm tot(tree)}$ are in keV. UV-complete theory: $m_S = m_F = 62.5$ GeV.

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Phenomenology

Phenomenological Constraints

- The UV-complete model is consistent with the $(g-2)_\ell$ measurement ($\lambda_{hs} y_\ell^2 = 0.72$ and $\lambda_{hs} y_\ell^2 = 28.1$ for $m_\Psi = m_S = 62.5$ GeV and 100 GeV, respectively).
- The UV-complete model satisfies electroweak precision tests.
- Collider constraints: $m_F \gtrsim 67$ GeV (within 5% uncertainty); the benchmark with $m_\Psi \gtrsim m_S = 62.5$ GeV is borderline, while $m_\Psi \gtrsim m_S = 100$ GeV is safe.
- $m_S = 100$ GeV is strongly excluded as a single-component dark matter candidate by direct detection, while $m_S = 62.5$ GeV remains viable due to proximity to the Higgs resonance.

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Conclusion

Conclusion

- There is background from $H \to \gamma\gamma$, tree-level bremsstrahlung, and box diagrams, which is cut-dependent.
- Appropriate kinematics cuts substantially reduce the background.
- EFT provides a possible explanation for the enhanced decay rate at the scale $\Lambda_R = 246$ GeV.
- There is a possible solution in terms of the UV-complete theory.
- The differential decay rate from the experiment is needed.
- Both the UV-complete model and EFT remain consistent with the current muon $g-2$ measurement, electroweak precision tests (EWPT), and collider measurements.
- Different kinematic cuts provide the possibility to constrain the model parameters.

Merci beaucoup!

Phenomenological constrains

Muon magnetic dipole moment

- Contribution to the muon's electromagnetic form factor $F_2(q^2)$ with q photon momenta

$$\Delta F_2(0) \hat{=} \Delta \left(\frac{g_\mu - 2}{2} \right) \hat{=} \Delta a_\mu = \frac{y_l^2}{192\pi^2} \frac{m_\mu^2}{M^2}$$

  is positive.
- For $y_\ell = 1.28$ and $m_S = 62.5$ GeV (corresponding to $\lambda_{hs} y_\ell^2 = 0.72$ if $\lambda_{hs} = 0.44$,is $\Delta a_\mu = 2.5 \cdot 10^{-9}$. A similar shift can be obtained with $y_\ell = 2.05$.
- For $m_S = 100$ GeV, corresponding respectively to $\lambda_{hs} y_\ell^2 = 28.1$ for $\lambda_{hs} = 6.7$.
- The Standard Model prediction for the muon anomalous magnetic moment is $a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \cdot 10^{-11}$, that lies within the range of the UV model prediction.

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Phenomenological constrains

Electroweak precision tests (EWPT)

- For $m = m_S = 62.5(100)$ GeV

$$\left.\frac{\Delta\Gamma}{\Gamma}\right|_{\rm inv} = 0.0002\,(0.00005) \; < 0.003$$
$$\left.\frac{\Delta\Gamma}{\Gamma}\right|_{\ell\ell} = 0.0002\,(0.00006) \; < 0.001$$
$$\Delta m_W = 0.0082\,(0.0026)\,{\rm GeV} \; < 0.013\,{\rm GeV}$$

- Oblique corrections are significantly smaller than the current 1σ experimental uncertainties.

Phenomenological constrains

Constraints from colliders

- Masses of Ψ and S are degenerate, with $m_\Psi \gtrsim m_S$.
- As the Yukawa coupling is not small, the process $\overset{(-)}{\Psi} \to S + \overset{(-)}{\ell}$ leads to soft leptons, which escape detection. The production of $\Psi\bar{\Psi}$ is thus equivalent to missing energy, $pp \to \text{jets} + \not{E}$.
- Collider detection limits can be estimated by comparing the processes $q\bar{q} \to Z' \to \chi\bar{\chi}$ and $q\bar{q} \to Z/\gamma \to \Psi\bar{\Psi}$.
- Bound: $m_F \gtrsim 67$ GeV (within 5%); benchmark with $m_\Psi \gtrsim m_S = 62.5$ GeV is borderline, while $m_\Psi \gtrsim m_S = 100$ GeV is safe.

Phenomenological constrains

Comments on DM direct detection

- In thermal freeze-out, the abundance $Y_S = n_S/s$ (with s the entropy density) scales as $Y_S \propto 1/\langle \sigma v \rangle \propto 1/\lambda_{hs}^2$.
- For the benchmark S particle with mass $m_S = 100$ GeV, thermal freeze-out requires a large quartic coupling: $\lambda_{hs} \gtrsim 2.2$.
- For S to account for all of DM ($f_S = 1$), one would instead need $\lambda_{hs} \approx 0.04$.
- If stable, the S particle would therefore be a subdominant DM component: $f_S \approx (0.04/2.2)^2 \approx 3 \cdot 10^{-4}$.
- This benchmark is excluded by direct detection. A lighter S particle, with m_S slightly above $m_H/2$, may still evade direct detection due to proximity to the Higgs resonance.

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